235279

UNITED STATES PATENT APPLICATION
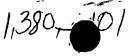
FOR

IMPROVED RE-Fe-B MAGNETS AND MANUFACTURING
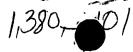
METHOD FOR THE SAME

BY

ANDREW S. KIM AND F. E. CAMP

LAW OFFICES
FINNEGAN, HENDERSON
FARABOW, GARRETT
& DUNNER
1300 I STREET, N. W.
WASHINGTON, DC 20005
1-202-408-4000

BACKGROUND OF THE INVENTION

Field of the Invention

The invention relates to a permanent magnet alloy for use in the production of permanent magnets.

Description of the Prior Art

Permanent magnet alloys, and magnets produced therefrom, are conventionally produced by combining a light rare earth element, preferably neodymium, with the transition element iron, and boron. Permanent magnets produced from these alloys exhibit outstanding magnetic properties at room temperature. The alloys, however, exhibit poor thermal stability and poor corrosion resistance, particularly in humid environments. Hence, this limits the applications for which permanent magnets of these alloy compositions may be used. Various alloy modifications have been proposed to overcome the problems of poor thermal stability and poor corrosion resistance. None of these modifications have resulted in improving these properties without sacrificing other significant properties.

OBJECTS OF THE INVENTION

It is accordingly a primary object of the present invention to provide a permanent magnet alloy and method for producing the same having improved thermal stability and corrosion resistance.

Another object of the invention is to provide a permanent magnet alloy and method for producing the same wherein improved stability and corrosion resistance is achieved, while improving the intrinsic coercivity without decreasing the remanence and Curie temperature to expand the useful temperature range for magnets made from the alloy.

SUMMARY OF THE INVENTION

In accordance with the invention, a permanent magnet alloy is provided consisting essentially of, in weight percent, 27 to 35, preferably 29 to 34 of a rare earth element, including Nd in an amount of at least 50% of the total amount of the rare earth element content, 0.8 to 1.3, preferably 0.9 to 1.2 B, up to 30, preferably 15 Co, 40 to 75 Fe, 0.03 to 0.3, preferably 0.05 to 0.15 C, 0.2 to 0.8, preferably 0.3 to 0.8 oxygen, up to 1, and preferably 0.5 of at least one of Cu, Ga and Ag. The alloy can further include up to 5 of at least one additional transition element selected from the group consisting of Al, Si, Sn, Zn, Nb, Mo, V, W, Cr, Zr, Hf, Ti, and Mg.

Cu, Ga and Ag may be present within the range of 0.02 to 0.5%, preferably 0.05 to 0.5%.

At least one of Pr or La may be substituted for up to 50% of the Nd. Likewise, at least one of Dy or Tb may be substituted for up to 50% of the Nd.

- 2 -

Co may be present within the range of 0.5 to 5%. Cu may be present within the range of 0.02 to 0.5%.

In accordance with the method of the invention, the above permanent magnet alloy is produced from prealloyed particles and/or blends of prealloyed particles. This may be achieved by the conventional practice of comminuting a casting of the alloy or atomization of the molten alloy as by the use of an inert atomizing gas in accordance with this well known practice. The prealloyed particles or blends thereof are contacted with a carbon containing material to produce a carbon content therein of 0.03 to 0.3% and preferably 0.05 to 0.15%. The carbon containing material may be a metal stearate, preferably zinc stearate. After contact with the zinc stearate, the size of the particles may be reduced by well known practices, such as jet milling. The particles are also contacted with an oxygen containing material to produce an oxygen content therein of 0.2 to 0.8% and preferably 0.3 to 0.8%. The oxygen containing material may be air. The particles may be contacted with air either during or after the size reduction thereof, including during a milling operation for reducing the size of the particles. The milling operation is preferably jet milling. The carbon-containing material and oxygen-containing material may be carbon dioxide.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a graph showing the demagnetization curves of the alloy 32.5 Nd, 0.1 Dy, 1.0 B, 66.4 Fe with oxygen contents of 0.41 and 0.24%;

Figure 2 is a graph similar to Figure 1, showing demagnetization curves of a 30.5 Nd, 2.5 Dy, 62.6 Fe, 2.5 Co, 1.1 B, 0.15 Cu, 0.65 Nb, having oxygen contents of 0.22 and 0.55%;

Figure 3 is a graph indicating the variation in H_{ci} for alloys of Nd-Dy-Fe-Al-B as a function of the oxygen content of the alloys;

Figure 4 is a graph similar to Figure 3, indicating the variation in H_{ci} for an alloy containing 29 Nd, 4 Dy, 5 Co, 1.15 B and balance Fe as a function of varying the oxygen content of the alloys;

Figure 5 is a graph showing the effect of varying Co with and without oxygen addition for an alloy of 30.5 Nd, 2.5 Dy, 1.1 B, 0.15 Cu, 0.65 Nb, and balance iron;

Figure 6 is a graph showing the effect of zinc stearate addition in varying amounts to increase the carbon content of an alloy of 31.9 Nd, 63.2 Fe, 3.6 Co, 1.15 B and 0.15 Cu;

Figure 7 is a graph showing the effect of varying the Cu content in an alloy of 33 Nd, 5 Co, 1.1 B, and balance iron;

Figure 8 is a graph showing the variation in the magnetic properties as a function of varying the copper

- 4 -

content in an alloy of 30.5 Nd, 2.5 Dy, 1.2 Co, 1.1 B, 0.5 Nb, and balance iron; and

Figure 9 is a graph showing the variation of magnetic properties as a function of varying the Nb content of the alloys 30.5 Nd, 2.5 Dy, 1.2 Co, 0.15 Cu, 1.1 B, and balance iron, and 28 Nd, 6 Dy, 2.5 Co, 1.1 B, 0.15 Cu, and balance iron.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

For purposes of development and demonstration of the invention, various alloys were prepared by conventional powder metallurgy processing and tested. Specifically, the alloys were produced by vacuum induction melting of a prealloyed charge of high purity elements and master alloys to produce a molten mass of the selected alloy composition. The molten mass was poured into a copper book mold or alternately atomized to form prealloyed powders by the use of argon as the atomizing gas. The cast ingot or atomized powder was hydrided at 1 to 30 atmospheres. The cast ingot was then crushed and pulverized into coarse powder. The pulverized powder or atomized powder was then ground into fine powder by jet milling with an inert gas such as argon or nitrogen gas. The pulverized powder or atomized powder was blended with various amounts of zinc stearate prior to jet milling to control the carbon content thereof and improve the

- 5 -

jet milling practice. Oxygen was added by slowly bleeding air into the system either during or after jet milling. The oxygen and carbon may also be added and controlled by exposing the powder to a CO_2 environment incident to these operations. The average particle size of the milled powders was in the range of 1 to 5 microns, as measured by a Fisher Sub-Sieve Sizer.

The prealloyed powder, prepared as described above, was placed in a rubber bag, aligned in a magnetic field, and compacted by cold isostatic pressing. The pressed compacts were then sintered to approximately their theoretical (full) density in a vacuum furnace at a temperature within the range of 900 to 1100°C for one to four hours. The sintered compacts were further heat treated at about 800 to 900°C for one hour and then aged within the range of 450 to 750°C. These magnet compacts were then ground and sliced into cylindrical shapes (6 mm thick by 15 mm diameter) for testing.

The magnetic properties of the magnets tested were measured with a hysteresigraph equipped with a KJS Associate's temperature probe at temperatures between room temperature and 150°C. The irreversible loss was estimated by measuring the flux difference with a Helmholtz coil before and after exposing the magnet at elevated temperatures of up

- 6 -

to 250°C for one hour. The permeance coefficient was one (1) because the L/D was 0.4 (6/15).

As may be seen from and will be explained in detail with respect to the tables and drawings, it was discovered that the addition of oxygen to permanent magnet alloy compositions in accordance with the description and claims hereof decreases the coercivity, as shown in Figure 1 with respect to the reported composition of (Nd,Dy)-Fe-B. When oxygen is added to a (Nd,Dy)-(Fe,Co)-B alloy, as shown in Figure 2, it increases the coercivity, with the remanence in both cases being increased by an oxygen addition. The causes of the increases in remanence by oxygen addition in both of these alloys were investigated. The saturation magnetization values of the magnets of these alloys measured by VSM are the same both with and without oxygen addition. To assess the grain orientation of these magnets, an experiment was performed on the alloy (Nd,Dy)-(Fe,Co)-B. A ground surface normal to the cylinder axis was placed in a Bragg reflecting configuration in an X-ray powder diffractometer. The diffraction patterns with and without oxygen addition to the alloy were obtained. When the magnet is a single crystal, or had an ideal orientation with the easy axis normal to the surface, the diffraction pattern would show only reflections (001) with even values of 1, namely (004) and (006) in the investigated range. The results are shown in Table I.

- 7 -

TABLE I
REFLECTIONS WITH LOW (h,k) AND HIGH l

hkl	Intensity	Misorientation $(h^2+k^2)/l^2$	Angle ϕ, degree	$\cos\phi$
004	9	0	0	1
114	9	0.125	26.1	0.898
214	89	0.31	37.8	0.790
105	50	0.04	15.5	0.966
115	25	0.08	21.4	0.931
006	25	0	0	1
116	8	0.055	18.1	0.951

The reduction of magnetization through misorientation is described by $\cos\phi$, which is given by

$$\cos^2\phi = l^2/[(c/a)^2(h^2+k^2)+l^2]$$

It was observed that sample A (without oxygen addition) exhibits strong (105) and (214) and relatively weak (004) and (006) peaks, while sample B (with oxygen addition) exhibits smaller (105), very weak (214), strong (004) and (006) peaks. This indicates that oxygen addition improves the grain orientation. Therefore, magnets with oxygen addition exhibit higher remanence than magnets without oxygen addition.

- 8 -

The effect of variation in oxygen content on the coercivity of both types of alloys was also investigated. Figure 3 shows the variation of coercivity for (Nd,Dy)-Fe-Al-B alloys, as a function of oxygen content. In this alloy system, the coercivity almost linearly decreases as the oxygen content increases. When the total rare earth content is lower, the H_{ci} decreases more rapidly.

Figure 4 shows the variation of coercivity for cobalt containing alloys, (Nd,Dy)-(Fe,Co)-Al-B, as a function of oxygen content. In cobalt containing alloys, the coercivity initially rapidly increases as oxygen content increases up to a point depending on total rare earth and other additive elements, and then starts to decrease with further increases in oxygen content. Because of this positive effect of oxygen addition in (Nd,Dy)-(Fe,Co)-B alloys, the negative effect of a Co addition reducing the coercivity will be diminished or minimized by the simultaneous addition of Co and oxygen. Therefore, a high T_c and B_r magnet with improved H_{ci} can be produced by the simultaneous addition of Co and oxygen in (Nd,Dy)-Fe-B alloys.

The effects of Co variation in a (Nd,Dy)-(Fe,Co)-B alloy were investigated with and without oxygen addition, and the results are listed in Table II. The variation of coercivities of the alloys with and without oxygen addition are plotted against cobalt content in Figure 5.

- 9 -

TABLE II
THE EFFECT OF Co VARIATION IN A
30.5Nd-2.5Dy-BAL Fe-1.1B-0.15Cu-0.65Nb-xCo
ALLOY WITH AND WITHOUT OXYGEN DOPING

	~0.2% O_2		~0.45% O_2	
% Co	B_r, kG	H_{ci}, kOe	B_r, kG	H_{ci}, kOe
0	11.30	20.2	11.65	19.8
1.2	11.45	20.2	11.65	20.8
2.5	11.20	18.3	11.30	20.4
5.0	11.40	17.3	11.50	17.6
15.0	11.45	13.9	11.55	14.9

As shown in Table II, the remanence increases 100-350 Gauss by oxygen addition to these alloys. The coercivity of non-cobalt containing alloys slightly decreases with oxygen addition, while that of cobalt containing alloys somewhat increases with oxygen addition. In alloys without oxygen addition, the coercivity decreases as cobalt content increases. In alloys with oxygen addition, the coercivity initially increases as Co content increases from zero to 1.2%, and then starts to decrease with further increases in Co content. Therefore, simultaneous addition of oxygen and a small amount of Co (1.2-2.5%) improves both remanence and

- 10 -

coercivity. Even at higher Co contents, the coercivities of oxygen doped alloys are still higher than those of the alloys without oxygen addition. Therefore, oxygen addition is essential for Co containing (Nd,Dy)-(Fe,Co)-B alloys. Since the T_c almost linearly increases with Co content, the required Co content in the alloy depends on Curie temperature, temperature stability and temperature coefficient of B_r. Generally, the Co content is preferred to be between 0.5 and 5%.

TABLE III
CHEMICAL COMPOSITIONS OF ALLOYS A, B, AND C BY WT. %

Alloy	Nd	Dy	Fe	Co	B	Cu	Nb	Al
(A)	31.5	0.5	bal	1.2	1.0	0.15	–	–
(B)	30.5	2.5	bal	1.2	1.1	0.15	0.35	–
(C)	28.0	6.0	bal	2.5	1.1	0.15	0.65	0.3

A few examples of improved magnetic properties and temperature stability (irreversible loss at elevated temperature) by oxygen addition are listed in Table IV. The chemical compositions of examined alloys are listed in Table III.

- 11 -

TABLE IV
MAGNETIC PROPERTIES AND IRREVERSIBLE TEMPERATURE
LOSS OF VARIOUS ALLOYS WITH AND WITHOUT OXYGEN DOPING

Alloy	% O_2	$\dfrac{B_r}{kG}$	$\dfrac{H_{ci}}{kOe}$	$\dfrac{BH_{max}}{MGOe}$	% Irr. Loss P.C. = 1.0
(A)	0.237	12.7	11.2	38.2	39.0% at 150°C
	0.574	12.9	14.9	40.2	3.6% at 150°C
(B)	0.123	11.7	16.8	33.2	20.8% at 175°C
	0.495	12.1	20.0	35.3	0.3% at 175°C
(C)	0.253	10.6	>20.0 (9.7 at 150°C)	27.5	8.3% at 200°C
	0.558	10.9	>20.0 (11.3 at 150°C)	29.3	1.8% at 200°C

As shown in Table IV, the magnetic properties (both B_r and H_{ci}) and temperature stability (irreversible loss) are substantially improved by an oxygen addition to Co containing (Nd,Dy)-(Fe,Co)-B magnets.

It is noted, however, that the coercivity starts to decrease when oxygen exceeds about 0.8% depending on the additive elements as shown in Figure 4. It is, therefore, necessary to limit oxygen content to between 0.2 and 0.8%, preferably 0.3 to 0.8%.

Since the magnets of the present invention were made by blending alloys with zinc stearate prior to jet milling, it is necessary to study the effect of variations of zinc stearate (carbon) on the magnetic properties. An alloy, $31.9Nd-63.2Fe-3.6Co-1.15B-0.15Cu$, was made by argon gas atomization. After hydriding, the powder was blended with different amounts of zinc stearate prior to jet milling as shown in Table V. The magnetic properties (B_r and H_{ci}) are plotted against zinc stearate variation in Figure 6. The variation of carbon content in the sintered magnets, density, remanence, and coercivity are also listed as a function of zinc stearate in Table V.

- 13 -

TABLE V
THE EFFECT OF ZINC STEARATE ADDITION TO
31.9Nd-63.2Fe-3.6Co-1.15B-0.15Cu ALLOYS

% ZS	% C	$\frac{D}{g/cc}$	$\frac{B_r}{kG}$	$\frac{H_{ci}}{kOe}$
0	0.036	7.39	12.2	9.6
0.05	0.073	7.57	12.7	12.3
0.1	0.094	7.53	13.0	12.15
0.2	0.150	7.56	13.2	11.1
0.3	0.184	7.57	13.25	9.3
0.5	0.310	7.56	13.5	7.7
0.8	–	not densified		

As shown in Figure 6, both the B_r and H_{ci} have significantly increased with small additions of zinc stearate. When the zinc stearate addition exceeds 0.1%, the H_{ci} starts to decrease while the B_r increases slowly. When the zinc stearate addition is 0.8%, the compact is not densified. Therefore, any zinc stearate employed for carbon addition should be limited to 0.5%. The carbon content of the sintered magnet almost linearly increases as the amount of zinc stearate added increases. Therefore, it is essential

to add small amounts of zinc stearate (carbon) for improving

magnetic properties (both B_r and H_{ci}). The optimum range of

zinc stearate addition is 0.05 to 0.2%, depending on the

magnetic property requirements. In the following study, the

zinc stearate addition was fixed at 0.1%, and oxygen was

added to about 0.5% in Co containing alloys.

Since it is known that the addition of 1 to 2% copper to

NdFeB melt spun ribbon substantially increased the

coercivity, we examined the effect of Cu variation in

sintered (Nd,Dy)-(Fe,Co)-B alloys. Figure 7 and Table VI

exhibit the variations of B_r and H_{ci} plotted against Cu

variation in a 33Nd-1.1B-5Co-(60.9-x)Fe-xCu alloy, and

corrosion resistance as a function of weight loss in relation

to the Cu content.

TABLE VI
THE EFFECT OF Cu VARIATION IN A
33Nd-1.1B-5.0Co-(60.9-x)Fe-xCu ALLOY

% Cu	$\dfrac{D}{g/cc}$	$\dfrac{B_r}{kG}$	$\dfrac{H_{ci}}{kOe}$	Wt. Loss (mg/cm^2)	
				96 hr	240 hr
0	7.58	12.8	9.4	17.5	228
0.05	7.58	12.9	10.8	0.5	4.7
0.1	7.58	13.0	11.3	0.7	2.2
0.15	7.58	12.9	13.0	0.07	0.08
0.2	7.58	12.8	13.5	0.01	0.16
0.3	7.58	12.65	13.2	0.05	0.42
0.5	7.57	12.65	12.4	0.15	0.25
1.0	7.48	12.3	11.5	0.19	0.36
2.0	7.36	12.3	9.0	0.52	0.76

As the copper content increases to 0.15%, the H_{ci} increases rapidly and reaches its maximum at 0.2% Cu. When the copper content exceeds 0.2%, the H_{ci} starts to decrease. The B_r also increases slightly as the copper content increases to 0.1%, and then slowly decreases with further

increases in copper content. Therefore, the overall change in remanence is negligible in the range of between 0 to 0.2% copper. A small addition of copper to Nd-Fe-B does not change the Curie temperature. These data indicate that a small addition of copper (up to 0.2%) to Nd-Fe-Co-B alloys substantially improves H_{ci} without reduction of B_r or T_c. The corrosion rate is significantly reduced as the copper content increases from 0 to 0.15% and the minimum corrosion rate is maintained with further increases in copper content.

Another set of magnets was made with oxygen doping to approximately 0.5%. Figure 8 and Table VII exhibit the variation of magnetic properties as a function of Cu content in 30.5Nd-2.5Dy-bal Fe-1.2Co-1.1B-0.5Nb-xCu alloy.

TABLE VII
THE EFFECT OF Cu VARIATION IN A
30.5Nd-2.5Dy-BAL Fe-1.2Co-1.1B-0.5Nb-xCu ALLOY

% CU	B_R	H_{ci}	BH_{max}
0	11.6	13.8	32.0
0.05	11.7	16.8	33.0
0.1	11.75	19.3	33.5
0.15	11.75	20.2	33.5
0.2	11.8	20.4	33.8
0.25	11.75	19.8	33.5
0.3	11.75	19.3	33.5

As the copper content increases to 0.1%, the H_{ci} increases rapidly then slowly increases to a maximum at 0.2% Cu. When the copper content exceeds 0.2%, the H_{ci} starts to decrease. The remanence and energy products also increase slightly as the copper content increases to 0.1%, and then remain the same with further increases in copper content to 0.3%. This indicates that a small addition of copper (between 0.1 and 0.3%) to oxygen doped (Nd,Dy)-(Fe,Co)-B alloys substantially increases H_{ci} with slight increases in B_r and $(BH)_{max}$. It is, therefore, beneficial to

simultaneously add small amounts of Cu, O, C (zinc stearate) to Co containing (Nd,Dy)-(Fe,Co)-B magnets in order to effectively improve coercivity without sacrifice of remanence.

It was observed that small additions of Ga or Ag to Co containing (Nd,Dy)-(Fe,Co)-B magnets might also substantially increase the coercivity similar to Cu. Examples of improved magnetic properties (H_{ci}) resulting from small additions of Cu, Ga, or Ag are listed in Table VIII.

TABLE VIII
CHEMICAL COMPOSITION AND MAGNETIC PROPERTIES

	Chemical Composition (Wt. %)								B_r kG	H_{ci} kOe
Alloy	Nd	Dy	Fe	Co	B	Cu	Ag	Ga		
D	31.9	-	bal	3.6	1.15	-	-	-	12.8	10.2
E	31.9	-	bal	3.6	1.15	0.15	-	-	12.9	13.0
F	31.9	-	bal	3.6	1.15	-	0.2	-	12.9	13.2
A	31.5	0.5	bal	1.2	1.0	0.15	-	-	12.8	15.2
G	31.5	0.5	bal	1.2	1.0	-	-	0.4	12.8	15.3

As shown in Table VIII, the coercivities are substantially increased by small additions (0.1 to 0.4 wt. %)

of Cu, Ag, or Ga to Co containing alloys (Nd,Dy)-(Fe,Co)-B, without reduction of remanence.

The effect of combined additions of these elements, Cu, Ga, and Ag, was also investigated. Alloys A (0.15% Cu) and G (0.4% Ga) were blended in different ratios, as shown in Table IX.

TABLE IX
THE EFFECT OF Ga AND Cu VARIATION IN A
31.5Nd-0.5Dy-BAL Fe-1.2Co-1.0B-xGa-yCu ALLOY

% Ga	% Cu	$\dfrac{D}{g/cc}$	$\dfrac{B_r,\ RT}{kG}$	$\dfrac{H_{ci},\ RT}{kOe}$
0	0.15	7.60	12.8	15.2
0.1	0.117	7.56	12.6	15.8
0.2	0.075	7.57	12.8	16.4
0.3	0.038	7.59	12.9	16.6
0.4	0	7.57	12.8	15.3

Although both alloys exhibit similar magnetic properties individually, when blended together the blended alloys exhibit higher coercivities. This indicates that when both elements Cu and Ga are used together, they effectively increase coercivity. The maximum coercivity was obtained when Ga content is 0.3% and Cu is 0.038%.

This concept was applied to 9% dysprosium alloys. By fixing copper content at 0.2, the Ga content was varied from 0 to 1.0%. The coercivities of these magnets were measured at 150°C.

TABLE X
THE EFFECT OF Ga VARIATION IN A
24Nd-9Dy-BAL Fe-2Co-1.1B-0.2Cu-0.65Nb-0.3Al-xGa ALLOY

% Ga	$\frac{D}{g/cc}$	$\frac{B_r, RT}{kG}$	$\frac{H_{ci}, 150°C}{kOe}$	Irr. Loss at 250°C (%) PC=1.0
0	7.54	10.1	15.7	16.1
0.2	7.53	10.2	16.5	2.0
0.4	7.47	10.05	16.9	3.1
0.6	7.42	10.0	16.3	2.9
0.8	7.33	9.9	15.9	4.4
1.0	7.31	9.5	15.3	9.0

As shown in Table X, the coercivity at 150°C increases as Ga content increases to 0.4%, and then starts to decrease with further increases in Ga content. The maximum coercivity was obtained when the Ga content is 0.4% and the Cu content is 0.2%. The irreversible losses at 250°C are very low when Ga content is between 0.2 and 0.6%, while magnets without Ga

- 21 -

or with 1.0% Ga exhibit relatively large irreversible losses. As the Ga content increases, the density starts to decrease. These data indicate that the optimum Ga content required for temperature stable magnets in this alloy system is between 0.2 and 0.6%. This is much lower than the Ga content necessary in (Nd,Dy)-(Fe,Co)-B alloys without O, C, and Cu addition if the same coercivity and temperature stability are required.

It is known to add 1 to 2 at. % (1.05-2.1 wt. %) Ga for similar enhancements. Therefore, single or combined additions of small amounts of M1 (Cu, Ga, or Ag) to the (Nd,Dy)-(Fe,Co)-(B,C,O) alloy effectively improve the coercivity without remanence reduction.

Additions of other transition metals (M2) including Al, Si, Sn, Zn, Nb, Mo, V, W, Cr, Zr, Hf, Ti, Mg, etc. to this alloy system, (Nd,Dy)-(Fe,Co,M1)-(B,C,O), further improve the coercivity with some reduction of remanence. As shown in Figure 9, for example, the H_{ci} increases and the B_r decreases as Nb content increases. Table XI displays magnetic properties of these alloys with various transition metals (M2) added.

TABLE XI
EFFECT OF M2 ELEMENTS ADDED IN
(Nd,Dy)-(Fe,Co,Cu)-(B,C,O) ALLOYS

Alloy	Wt. %							B_r kG	H_{ci} kOe
	Nd	Dy	Fe	Co	B	Cu	M2		
H	30.5	2.5	bal	1.2	1.1	0.15	-	12.3	18.5
I	30.5	2.5	bal	1.2	1.1	0.15	0.2Al	12.0	20.4
J	30.5	2.5	bal	1.2	1.1	0.15	0.75Si	11.4	20.3
K	30.5	2.5	bal	1.2	1.1	0.15	0.65Nb	11.7	21.0
L	31.2	2.5	bal	1.2	1.1	0.15	0.2Al + 0.65Nb	11.4	21.5

A part of Nd in this alloy system can be substituted by other light rare earth elements, including Pr, La. Table XII exhibits magnetic properties of this alloy system in which Nd is partially substituted by Pr or La.

TABLE XII
MAGNETIC PROPERTIES OF RE-(Fe,Co,Cu)-(B,O,C) ALLOYS WITH PARTIAL SUBSTITUTION OF Nd WITH OTHER RARE EARTH ELEMENTS

	Wt. %									B_r kG	H_{ci} kOe
Alloy	Nd	Pr	La	Dy	Fe	Co	B	Cu	Nb		
M	30.5	-	-	2.5	bal	1.2	1.1	0.15	0.35	11.9	20.2
N	26.5	4.0	-	2.5	bal	1.2	1.1	0.15	0.35	12.0	20.1
O	28.8	-	1.6	2.5	bal	1.2	1.05	0.2	-	11.9	18.3

As may be seen from the above-reported specific examples, (Nd,Dy)-(Fe,Co)-B magnets doped with small amounts of oxygen and/or carbon, which may be achieved by zinc stearate addition, exhibit much higher magnetic properties (both B_r and H_{ci}) than (Nd,Dy)-(Fe,Co)-B magnets without oxygen and/or carbon addition. Small additions of Cu, Ga, Ag, or a combination of these (M1) to (Nd,Dy)-(Fe,Co)-(B,C,O) substantially increases the coercivity without reduction of remanence. Since the coercivity is substantially improved without reduction of T_c and/or B_r in this alloy system, it can be used at elevated temperatures with minimum additions of Dy. Utilization of abundant and inexpensive elements such as O, C, Cu and reduction of expensive elements such as Dy

and/or Ga will reduce the total cost of producing magnets from this alloy system. The coercivity can be further improved with additions of other transition metals (M2) including Al, Si, Sn, Zn, Nb, Mo, V, W, Cr, Zr, Hf, Ti, and Mg. Additions of these elements will, however, cause reduction of remanence and energy product. Other light rare earth elements such as Pr or La can partially replace Nd in this alloy system.

As used herein, all percentages are in "weight percent," unless otherwise indicated.

The following conventional abbreviations are used herein with respect to the reported properties of magnets:

B_r - remanence

H_{ci} - intrinsic coercivity

BH_{max} - energy product

T_c - Curie temperature